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Using design information to create a data framework and tool for life cycle analysis of complex maritime vessels

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ABSTRACT

Maritime vessels are complex products with long service lives and high costs of construction, manning, operating, maintaining and repairing. The definition of a consistent and repeatable life cycle model among vessel types is still an open question, and the development of such a model can be helpful for the implementation of decision-making strategies and design choices. The present paper aims to introduce a life cycle model and a data framework in the early phases of shipbuilding design, supporting the decision-making process of material selection, manufacturing and assembly processes, maintenance and service, use and end-of-life. The model provides a common structure for life cycle assessment (LCA) and life cycle cost analysis (LCCA), including an approach to retrieve and collect all data necessary for the analysis starting from the available project documentation and design models. Three luxury yachts with different features were analysed using the proposed model, and a software tool that embeds the developed data framework was developed. The results provided by the tool are in line with the same analyses carried out with dedicated LCA and LCCA tools (maximum deviation of 6.3% for climate change indicators). Other important advantages are (i) the time saved for the inventory phase, (ii) compliance with existing life cycle standards (e.g., ISO 14040), and (iii) the possibility to make comparisons and a benchmarking analysis.

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1. Introduction

The construction of large, complex and low volume products like ships, ferries and offshore vessels is a multidisciplinary and long process that includes many activities until the product delivery (design phase, construction phase, etc.). It is widely known that decisions made during the early design phases have a great impact throughout the entire life cycle in terms of costs, performance, sustainability, etc. (INA, 2013; US GAO, 2000). The adoption of a life cycle approach enables addressing these aspects in the design phase, providing useful indicators (Tincelin et al., 2007).

Even though the adoption of life cycle disciplines has become widespread in many industries (e.g., chemistry, materials production plants), life cycle analysis faces several problems in the shipbuilding context. First, it requires the management of a huge amount of different data generated by different stakeholders (designers, external suppliers, ship owner, etc.). In particular, inventory and data collection are extremely time consuming because the data exist in different formats (files, documents, etc.), are stored in different repositories (PLM, CAD, etc.) and become available in different phases of the project development. Second, life cycle analysis requires a high degree of expertise necessary to perform the analysis and to translate results to robust design choices. This problem is particularly relevant for the environmental aspects.

The aim of this paper is to define a model and a data framework for the life cycle analysis of large and complex maritime vessels, including both environmental and cost impacts. A data framework is filled using design information and by retrieving inputs from the project design documentation (excel files, technical data sheets, CAD models, etc.). In particular, the objectives of this research are as follows:

- to develop a robust model for life cycle evaluation of different vessel types (including functional unit, system boundaries, etc.) that is compliant with the existing standards (e.g., ISO 14040);

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- to establish a common framework for data collection starting from available project documentation (project files, CAD models, etc.) that enables the performance of benchmark analyses; and
- to define a link with traditional design tools for an efficient data feed, avoiding error-prone and time-consuming activities (i.e., life cycle inventory).

The model and the data framework have been developed to be consistent among the different vessel types and repeatable in different contexts with the same level of detail. Their main novelty is their ability to be used as a basis for the development of product-specific life cycle tools oriented to the assessment of life cycle performances and to support the decision-making process of designers and engineers (material selection, manufacturing processes, equipment, etc.).

The paper is structured as follows: following the *introduction*, the *background* section provides an overview of the other research studies in this field. The *materials and methods* section describes the LCA/LCCA model developed for shipbuilding application, the data framework and the approach for the development of the software tool. Three different models of luxury yachts are proposed and analysed as *case studies*, and the main results obtained are reported and discussed in the *results* section. Finally, the *discussion and conclusions* are presented.

2. Background

Shipbuilding is recognized as one of the larger and more profitable industries in the world. Despite the traditional nature of this industry, market requirements and new legislative frameworks have increased the level of innovation towards sustainability in this sector. Shipbuilding products are seagoing vessels that are different in types and classes, and this distinction is based on their end-use and operational activities (Fig. 1) (Favi et al., 2018).

Maritime vessel classifications are established and assigned by the recognized classification societies (e.g., IMO), which also approve surveys and inspections aimed to meet a minimum set of regulatory, technical, environmental and safety requirements. Ship design is a challenging activity in the development of such a complex project, and life cycle engineering plays a key role in the development of more sustainable maritime means, which have long lifespans and different operational scenarios (Hall et al., 2006; Basurko and Mesbahi, 2014). Starting in recent decades, Product Life cycle Management (PLM) and Product Data Management (PDM) have become popular in shipbuilding as design suites for project management (Lee and Lee, 2014; Cang et al., 2013). These systems have been used to close the gap between ship design and shipbuilding, encouraging design collaboration and efficient data sharing (Sharma and Kim, 2010; Andrade et al., 2015). However, their use is limited to the project lifetime, which ends at the vessel delivery (Turan et al., 2009).

A life cycle analysis implies an approach considering the life cycle which goes further than cost estimation and project management (Landamore et al., 2007). Life cycle analysis approaches analyse the cost and environmental impacts with a holistic approach throughout the entire life cycle (Cabezas-Basurko et al., 2008). Life Cycle Assessment (LCA) is a consolidated approach for environmental assessments of products and services, addressing the potential environmental impact of a product or service from a cradle-to-grave perspective (ISO, 2006a; ISO, 2006b). Life Cycle Costing Analysis (LCCA) is a well-known method in this field for assessing the total cost of ownership, including the operational and running costs (e.g., fuel consumptions, service/maintenance, etc.) (ISO, 2011; Dinu and Ilie, 2015).

LCA and LCCA are complementary analyses that are based on different assessment methods, albeit with common aspects. The breakdown of life cycle phases is similar for costs and environmental impacts, and the overall frameworks (steps) used to perform the analyses (e.g., goal and scope definition, inventory, assessment and interpretation) are similar as well (Kameyama et al., 2007; Zhang et al., 2017). Life Cycle Inventory (LCI) is a critical step of both analyses for this kind of product. LCI requires a large effort in terms of time and resources to sort, collect and harmonize the data, which are used as input for the two models. Usually, this activity is performed by external experts and requires (i) interviews of company engineers/designers, (ii) an in-house measurement campaign and, (iii) analysis of project documentation. Some researchers have demonstrated how the integration of an LCA/LCCA framework with Computer Aided Design tools (CAD) provides tangible support in the compiling of the LCI data (Tao et al., 2017; Morbidoni et al., 2011).

An analysis of the literature highlights several examples of LCA tools developed in the shipbuilding context. For example, the Royal Institution of Naval Architects (London - UK) has proposed a dedicated tool to assess the environmental impact of ships for use in the marine industry (Tincelin et al., 2007). In this case, weight, cost and power consumption estimations are out of the scope of

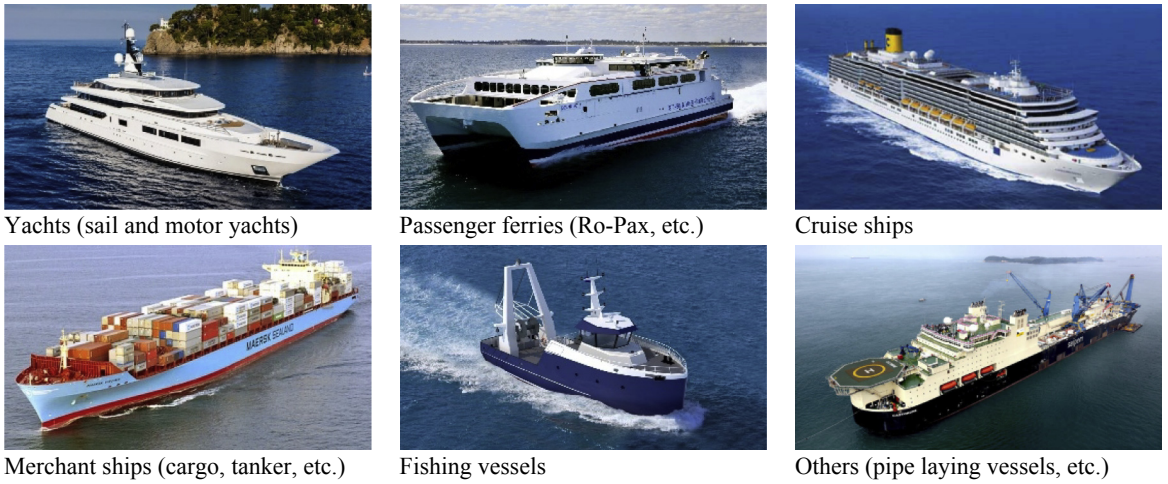


Fig. 1. Main vessel types.

this software and are supposed to be calculated by the traditional design tools of the naval architect. Another interesting tool for the life cycle assessment of ships has been developed by the Centre for Naval Architecture Royal Institute of Technology (Stockholm - SE) (Alvestad, 2012). This tool provides front-end design support, and therefore, focus is placed upon achieving reasonable results with little and possibly imprecise input data. The aim is thus not to provide precise estimates of environmental impacts but to note the design alternatives that are better off with limited effort in benchmarking and comparison analysis.

Both of these methods do not allow the performance of a life cycle inventory in an easy and automatic manner, leaving this problem to the naval engineers and architects. Currently, no tool has been developed in the shipbuilding sector to support the inventory phase, which is considered a tedious and error-prone activity. In addition, the level of detail and the quality of results are entrusted to the specific needs of each shipbuilding company, providing results that cannot be subsequently used for comparison or benchmarking analysis.

The development of life cycle data models for industrial applications appears to be beneficial to assist environmental analysis, and they can be the basis on which to develop specific supporting tools (Goepp et al., 2014; Sandberg et al., 2017). In particular, these models envisaged the creation of complex data structures, which gather heterogeneous information used throughout the life cycle of a product (Borsato, 2014). For this reason, specific taxonomy is needed to include key entities and their features starting from real data available from the field (Cerri and Terzi, 2016).

State-of-the-art analysis shows that the LCA/LCCA methods have only been used to a limited extent in seaborne transportation means. Several issues have been identified in the literature for the application of LCA/LCCA in shipbuilding:

- Life cycle methodologies are fragmented, and the quality of results varies among different shipbuilders (Borsato, 2014; Utne, 2009; Favi et al., 2017);
- Available LCA/LCCA tools are customized based on the shipbuilding purposes and cannot be used to reach accurate results in benchmarking and comparative analysis (Tincelin et al., 2007; Favi et al., 2018; Alvestad, 2012);
- LCI requires the involvement of environmental experts and access to several documents stored in different repositories (Tchertchian et al., 2013); and
- LCI represents the critical phase, and an integration with the traditional design tools (CAD, PLM, etc.) would be beneficial to reduce time and errors (Gratsos et al., 2009).

The identification of these barriers provided an additional boost to the research in this field, with the aim to establish a practical and standardized approach for the evaluation of marine transportation. The lack of a data framework for robust and shared life cycle inventory is recognized as the main bottleneck in this sector.

3. Materials and methods

This section aims to describe (i) the life cycle model (section 3.1) for performing a structured and robust LCA/LCCA analysis in shipbuilding applications, (ii) the data framework (section 3.2) developed to assist life cycle inventory by using the design information, (iii) the engineering approach (section 3.3) for integration of model and data framework in the design loop of complex vessels, and (iv) the approach to implement a software tool (section 3.4) starting from these premises.

3.1. LCA-LCCA model and analysis

ISO standards have been used as a reference for the definition of the life cycle model. ISO provides a structured framework through a number of standards aimed at quality and transparency as well as requirements for internal and published life cycle studies. In particular, the assessment of environmental impacts is derived from the consolidated methodology of ISO 14040:2006 and ISO 14044:2006 (ISO, 2006a; ISO, 2006b). The assessment of life cycle cost is derived using the methodology developed for buildings and asset applications (ISO-15868:2011) (ISO, 2011). Although the objectives and the results of these standards are different, they are based on the same framework. Thus, a common model for the life cycle analysis (both economic and environmental) can be developed based on this framework. Moreover, economic and environmental assessment uses the same lifetime discretization. Some differences can be noticed considering the items involved in the two analyses. For example, crew and insurance are relevant items for the life cycle cost but are not relevant to the environmental aspects.

Based on the above, the LCA and LCCA models can be divided into 4 phases, as depicted in Fig. 2.

The first step of the model is the setting of the *Scope*, which is the basis for each life cycle analysis. The scope phase requires the definitions of "*functional unit*", "*reference flow*" and "*system boundaries*".

Functional unit is a key aspect for the execution of a life cycle analysis. In this case, it can be defined as "*the construction and the disposal of a vessel for the transportation of persons and goods and/or operational activities by sea for a period of T years*", where T represents the lifespan of the product. Functional unit can be amended accordingly if one or more phases are excluded from the analysis. In this case, vessels comparisons are possible only for the vessels that have the same functional unit.

Reference flows translate the abstract functional unit into specific product flows of the vessel under analysis. Typically, the reference flow is the parts list (bill-of-materials) of the product multiplied by a factor to scale it to the functional unit. The reference flows are the starting points for building the necessary models of the product system.

System boundaries allow the definition of the inputs and output for each phase of the vessel life cycle. The system boundaries adopted for this model are shown in Fig. 3 and contain (i) materials and manufacturing phase, (ii) use phase and, (iii) end-of-life.

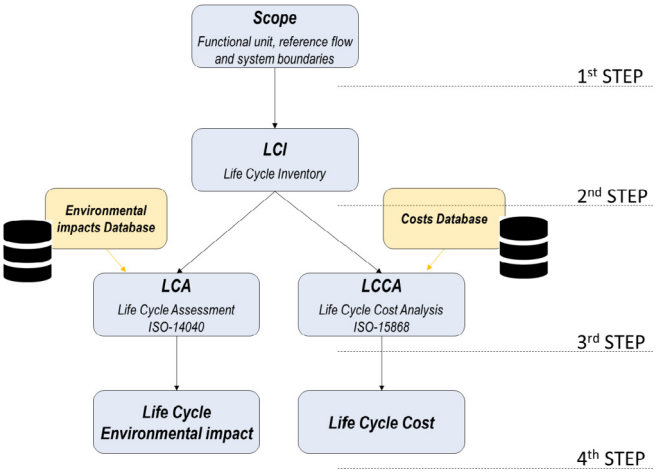


Fig. 2. Life cycle model for the assessment of maritime vessels.

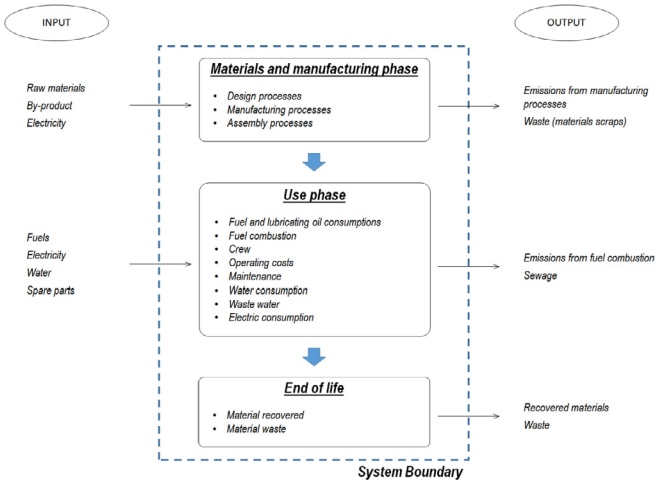


Fig. 3. System boundaries.

Materials and manufacturing includes the design of the vessel, and all the construction activities (manufacturing processes, assembly, etc.) necessary to build the vessel starting from raw materials. Use phase begins at vessel delivery and lasts until its disposal. Several items are involved in the use phase such as the fuel necessary for navigation and operational activities, components which require periodic maintenance, and electric energy and water consumed at the pier during the berthing periods. End-of-life is the last phase during which the vessel is decommissioned, and different options can be available such as material recycling and/or vessels' sinking.

Once the functional unit, reference flow and system boundaries are defined, the Scope of the analysis is clear, and the first step of the method is completed.

Life cycle inventory (*LCI*) is the second step of the model. This step requires the quantification of flows (inputs and outputs) and involves the collection of heterogeneous data from different sources. Each flow refers to a specific life cycle stage. A detailed list of inputs required for the analysis is reported in Appendix A. The list is split based on the life cycle stages and contains (i) item, (ii) required data, (iii) data type, and (iv) data source. It is important to note that some inputs (e.g., material types, quantities, cutting/welding lengths) can be read automatically from the two master documents, such as the "lightship-weight" document or the "3D CAD model", and other inputs (e.g., engine and generator performances) must be managed by the adoption of use scenarios in order to obtain the correct values through the whole life cycle. Use scenarios can be manually defined; otherwise, pre-set scenarios can be chosen from a list (e.g., specific routes for cruises, port connections for ferries, etc.).

The evaluation of life cycle performances (both *LCA* and *LCCA*) is the third step of the model. This phase starts by using the inputs provided in the previous step (design data collected during the inventory) and customized methods (algorithms) able to connect these inputs with dedicated databases of unitary costs and environmental impacts (background data). The use of *LCA* and *LCCA* methods allows to link the design data with the background data for the assessment of life cycle performances (both economic and environmental). In this step, *LCA* and *LCCA* differ in terms of (i) methods adopted for environmental impacts calculation and life cycle cost and (ii) used database for background data.

For the LCA calculation method, an appropriate life cycle impact assessment (LCIA) method needs to be defined to quantify the magnitude and significance of the potential environmental impacts in accordance with the LCA standard. The selection of the most suitable LCIA method is mainly related to the characteristics of the system under analysis. In particular, the environmental impacts have been calculated according to the following life cycle impact assessment (LCIA) methods:

- ReCiPe midpoint – Hierarchist (H) version – Europe (Goedkoop et al., 2009)
- Cumulative Energy Demand (CED) (Jungbluth and Frischknecht, 2010)

Since this study is oriented towards the shipbuilding and transportation sector, materials, energy and natural resources as well as the emissions related to the combustion of non-renewable resources are of primary importance. To address these perspectives, this study uses midpoint impact categories connected to the Human Health (HH) and Resources (RA) end-point impact categories as described in the ReCiPe document report (Goedkoop et al., 2009). The default ReCiPe midpoint method perspective used is the Hierarchist (H) version. This choice has been made based on the most common policy principles with regard to the 100 [year] timeframe (as referenced in the ISO 14044:2006 standards on LCA). The cumulative energy demand (CED) method (Jungbluth and Frischknecht, 2010) is also used as a single-issue indicator to evaluate the energy demand associated with a product's life cycle.

Finally, the global environmental impact is given by the sum of the environmental impacts of the three life cycle phases:

$$I_t = I_m + I_u + I_e. \quad (1)$$

Here, I_m is the impact of the construction phase, which takes into account the raw materials extraction, manufacturing processes (in-house and/or related to by-products) and assembly operations. I_u is the impact of the use phase and contains the environmental load derived from fuel and oil consumption, the greenhouse gas emissions related to the fuel combustion, maintenance and parts substitution, water and electricity consumption, and wastewater production. I_e is the end-of-life impact, which takes into account the benefits of material recovery and the impacts of material waste (e.g., landfilling or sunk). The end-of-life (EoL) phase is included in the LCA analysis and has been modelled following the "0:100, no credit, closed loop assumed" (Allacker et al., 2017). In this case, the recycling of scrap generated by the production system has not been part of the product system, and no credits have been given for subsequent recycling. The choice of this approach was derived from a high level of practicality, as it does not require one to estimate the impact due to recycling of product at end-of-life nor to estimate the avoided virgin production due to recycling at end-of-life. Burdens have been included for the landfill process for the remaining fraction of materials. The fraction of material flowing directly to disposal has been derived considering the typical recycling rate for several material classes as indicated in literature (Mikelis, 2013; International Aluminium Institute, 2009; Schmidt, 2012).

For the LCCA calculation method, the standard requires the possibility to add and compare cash flows that are incurred at different times. To make the cash flows time-equivalent, the LCCA method converts them to present values by discounting them at a certain point in time. The interest rate used for discounting is a rate that reflects an investor's opportunity cost of money over time. Hence, the discount rate represents the investor's minimum acceptable rate of return. Since this study is oriented to a product with a long service life (more than 20 years) with several cash flows over time, net present value can be used as a cost impact assessment method, and the global life cycle cost is calculated as:

$$C_t = C_m + \sum_{t=0}^{T} \frac{C_{ut}}{(1+i)^t} + \frac{C_e}{(1+i)^T} \quad (2)$$

Here, C_m is the construction phase cost, and takes into account design and engineering costs, the costs of by-products and raw materials, and the assembly and manufacturing activities costs. C_{ut} is the cost associated with the t-th year of the use phase and collects the costs related to maintenance, fuel and oil consumption, crews payroll, assurance and berthing. C_e is the cost/benefit related to the end-of-life. Finally, T is the vessel's lifespan, consistent with the lifespan stated at the time of functional unit definition, and i is the discount rate.

The following dedicated repositories for background unitary data are required: (i) Costs Database and (ii) Environmental impacts Database.

For the implementation of the Costs Database, unitary raw materials costs can be retrieved from open-source repositories and websites, such as the London Metal Exchange (London Metal Exchange, 2018) and ASSOMET (Associazione Nazionale Industrie Metalli non Ferrosi, 2018). Costs of by-products (e.g., engines), which are purchased from suppliers, can be collected by interview and quotation of the different suppliers. Assembly, manufacturing and production costs are more difficult to retrieve and to assess. Usually, they may depend on the construction and assembly site of the ship and are treated as confidential data by the shipyard. However, these costs can be estimated based on historical data and previous projects. The Costs Database can be updated, including the possibility of addition of new items when necessary.

For the implementation of the Environmental Impacts Database, commercially available LCA repositories (e.g., EcoInvent) can be used and adopted. The EcoInvent database provides documented process data for thousands of products and materials, which are classified as "dataset" (Frischknecht et al., 2005). A limited share of the EcoInvent database has been used, including main construction materials (e.g., metals, plastics, composites), natural resources (e.g., water, fuels, electricity) and by-products used in shipbuilding applications (e.g., lights, electronic equipment, switchboards, etc.). In addition, ad hoc processes (e.g., welding, cutting) have been modelled as new "datasets" by using state-of-the-art and internal knowledge. The intent to use a limited portion of the EcoInvent database improves the efficiency of the study at the cost of precision. Neglected items in the Environmental Impacts Database do not lead to a change in the shipbuilding design and do not affect the final guidance. Neglected aspects are mainly related to owner customization (e.g., accommodations). For the LCCA database, the costs database can be updated, and new items can be added as required.

Lastly, *Life cycle environmental impacts* and *life cycle cost* (4th step) are calculated and are displayed for interpretation and analysis.

3.2. Definition of life cycle data framework

LCI is considered the most problematic and time-consuming step of the model for such a complex product, in particular if it is performed during the design phase. Thus, the aim of a structured data framework is to facilitate the drawing of data input/output as well as to standardize the inventory phase in this field. For each one of the three phases of the vessel's life, the framework identifies the sources from which it is possible to retrieve the available data and provide the mathematical relationships necessary to obtain all input and output flows through the system boundaries (see Appendix A). Data framework has been defined with the same structure independently from the vessel types.

3.2.1. Materials and manufacturing phase

Based on the vessel classification, a common hierarchical structure of all the constituent elements of the ship (modules) has been developed. It consists of eight main groups, with each one subdivided into several other subgroups. The groups and subgroups breakdown is mainly based on functional criteria and literature analysis (Alvestad, 2012). The eight main groups are represented in Fig. 4 and can be described as follows:

- *Hull and superstructure*: contains all structural elements of the hull and the superstructure of the ship.
- *Outfitting*: contains the main outfitting necessary for the vessel's operational activities. This group is characterized by all elements that distinguish one type of ship from another.
- *Machinery and propulsion*: contains all elements that contribute to the power generation and mechanical propulsion of the ship.
- *Electrical navigation and communication*: contains electronic equipment for vessel control, from radar systems to indoor entertainment, plus all wiring required to convey electrical power across the ship.
- *Piping system*: contains all piping systems in the ship, from sewage to the fire system.
- *HVAC*: contains heating, ventilation and air conditioning systems.
- *Accommodation and finish*: contains all items of the ship related to the accommodation of the crew and guests.
- *Painting and insulation*: contains materials used for the vessels insulations and aesthetical finishing (including anti-corrosion systems). This group also contains chemical substances used for painting the ship and its protection from corrosion and marine algae and fauna (antifouling).

The classification and grouping process has a dual function. The first one is to simplify the data collection and the application of LCA/LCCA methodologies by grouping of the elements of a similar nature. The second one is to simplify the analysis of results, enabling easy switching from general to detailed information and thus identifying the most problematic functional area of the vessel.

The subcategories of this hierarchical structure must have a list of all the elements of the ship and their quantities. Such a list can be obtained from the design documents such as the "lightship-weight" document. "Lightship-weight" is the weight of the ship without passengers, fuel, cargo, water and all the consumables on board. In addition to the list of components and their constituent materials, it is also necessary to identify the main shipbuilding operations. Typically, the main construction activities performed at a shipyard are those related to hull and superstructure manufacturing, which are metal carpentry processes (e.g., sheet metal cutting and welding) for metal structures and/or fibre reinforced composite forming/moulding (e.g., hand lay-up, vacuum infusion) for composite structures. In both cases, a set of process

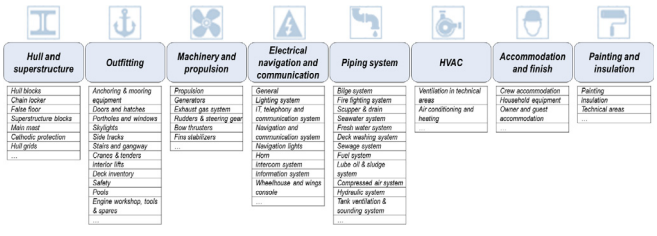


Fig. 4. Hierarchical structure for the classification of the vessel's items.

parameters are necessary in order to perform a life cycle analysis. For metal structures, the following inventory data are available and can be retrieved by exploring the "3D CAD model": (i) the overall length of edges which require cutting operations, (ii) the size and the geometry for the bevel preparation and, (iii) the length of welding beads. In addition, by analysing the "welding map" document, it is possible to obtain the missing data to perform the inventory of the welding processes. Thus, by coupling both project files ("3D CAD model" and "welding map"), all useful data for the life cycle inventory of cutting and welding operations are available. On the other hand, for composite structures, the data related to the manufacturing process are available by consulting the "manufacturing manual" in which the process features such as the required time for manufacturing operations are stored.

3.2.2. Use phase

When the life cycle analysis is performed during the ship design, the use phase is not known with certainty. For this reason, inventory data for this phase must be assumed by defining use scenarios. Use scenarios allow a complete overview of the possible environmental and economic impacts of the vessel through its entire life. Operative scenarios do not guarantee the same level of uncertainty for different vessel types. Indeed, the use phase of "private" vessels (yachts, fishing vessels, etc.) is generally affected by a high level of uncertainty, while "public" vessels (passenger ferries, etc.) have an established use phase. In any case, the definition of use scenarios is based on the ship owner requirements and is a prediction of the vessel use (navigation hours, speed, berthing periods, etc.). Use scenario information is combined with engine manufacturers' data (engine power, performances, fuel consumptions, etc.) to quantify the input/output flows necessary for the inventory characterization. The "technical datasheet" provided by the engine manufacturers is the project document that can be handled to retrieve and draw the inventory for the gas emissions and fuel consumptions. Use scenarios can be hypothesized from the information already known at the time of the analysis and provided by the vessel's owner. In addition, these data can be coupled with the vessel's features such as vessel type, weight, motors' and generators' performances, maintenance activities, etc. This kind of a link allows the creation of pre-defined scenarios, which are very useful to automatically fill the model data framework for the use phase.

An important issue to face in this phase is related to the time horizon of the vessels. Indeed, ships are supposedly designed for a 20–25 year life, which is typically the corrosion allowance of structural parts (e.g., hull) as described in most of the international associations and classification societies (e.g., IMO). In such a long timeframe, the expected vessel lifetime may differ due to the external factors, contingencies, etc. that represent the main causes of uncertainty for the proposed model. Repurposing or refurbishment are possible for large vessels (e.g., tankers, cruisers, ferries), while demolition or sinking are adopted for small and private ships (e.g., yachts, fishing vessels). In particular, repurposing and refurbishment represent a random variable and cannot be taken into account in the use phase model.

Six main groups involved in the definition of the vessels' use phase have been identified, as shown in Fig. 5 and summarized as follows:

- *Fuel and lubricating oil*: concerns fuel consumption for propulsion and electricity production;
- *Crew*: concerns the costs related to the personnel;
- *Operating costs*: concerns the costs of berthing and assurance;
- *Maintenance*: concerns the costs and resources necessary for the periodic maintenance of the vessel;

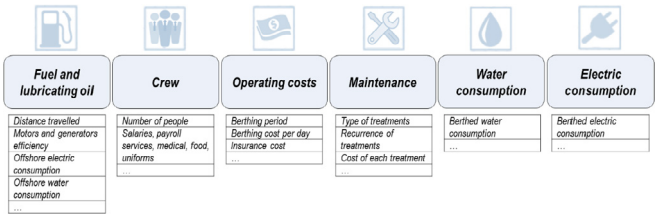


Fig. 5. Main groups for the use phase.

- *Water consumption*: concerns the consumption of drinking water from the network. This group excludes the consumption of water produced on-board the ship through the desalination plant;
- *Electric consumption*: concerns the electric consumption from the grid; in this case, the consumption is limited to mooring periods.

Crew and *Operating costs* groups differ from the other groups because no environmental impact can be attributed to these groups. Indeed, they are not associated with material or energy flows but only services.

Identified groups, together with the mathematical relationships that allow the estimation of the required values from the data available during the design of the vessel, constitute the data framework for the use phase (see Appendix A).

3.2.3. End-of-life

Vessel end-of-life is difficult to model because it is the furthest phase in the future from the time of the analysis, and therefore it is affected by a great degree of uncertainty. Vessel end-of-life is the responsibility of the ship owner, which should ensure that the process is in compliance with current legislation. Currently, 97% of the ships are dismantled in 5 countries: India, Bangladesh, Pakistan, China and Turkey (Pulli et al., 2013). This is mainly due to the lower labour costs and high steel demand in these developing countries. Here, the dismantling process often occur in unclear conditions. Smaller vessels are often are simply abandoned and sunk rather than dismantled (Richards, 2013).

Because of the high uncertainty of this phase, in the first approximation, the inventory phase can be performed by assuming different end-of-life scenarios, such as sinking, or material recovery after disassembly. In the case of the disassembly scenario, recovered materials may be considered as a percentage of the raw materials constituting the vessel (Pulli et al., 2013), or as a percentage of the lightship weight (Hess et al., 2001). The use of approximate data and models is the only feasible approach for accounting for the effect of end-of-life options in the whole life cycle.

3.3. Life cycle model and data framework in the design loop

A life cycle model data framework has been coupled to create an engineering approach, which can be integrated in the design loop for a generic vessel development. Fig. 6 describes the design workflow, including both the life cycle model (highlighted in blue) and the data framework (highlighted in green).

Environmental impact evaluation shall be performed on a preliminary design and using project documentation available in the preliminary design phase. As described above, the project documentation that is available at the design phase consist of the following:

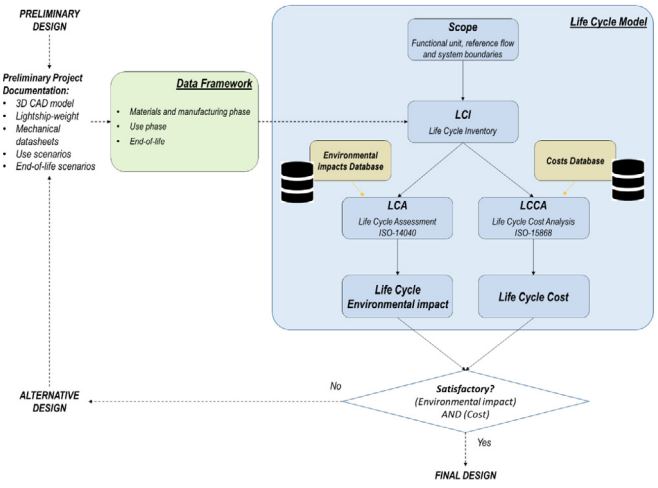


Fig. 6. Integration of "Data framework" and "Life cycle model" in the design loop.

- the "lightship-weight", which can be considered the master document of the analysis;
- the "3D CAD model", which includes the geometrical information for the manufacturing processes;
- the "welding map", which represents a drawing of the assembly to be welded showing the location of each weld and the unique identifying number;
- the "manufacturing manual", which defines the time-related aspects of the manufacturing processes;
- the "technical datasheets" for engines and generators, which report fuel consumptions in different operative working points;
- the "use scenarios", which are set based on the vessels' owner requirements; and
- the "end-of-life scenarios", which are set based on the current legislation and practice in the field.

All these documents are "read" by the data framework and opportunely sorted and managed to fill out the inventory, which is based on the *Scope* defined within the model. Inventory data and primary data from databases (Environmental impacts Database and Costs Database) are combined with the proposed calculation methods (Eqs. 1 and 2) to perform the LCA and LCCA assessments.

If the life cycle results (both economic and environmental) are not satisfactory, an alternative design can be developed, focusing the design efforts on the most impactful areas highlighted by the analysis. Then, the process can be repeated until satisfactory results are obtained. Then, the configuration of the vessel is finalized, and the manufacturing/construction activities can occur.

3.4. Tool architecture and implementation

Based on the proposed life cycle model and using the defined data framework, it is possible to implement a software tool dedicated to the life cycle analysis of maritime vessels. The software tool has the purpose to assist end-users in the process for preparing the data framework, facilitating the data editing and importing from different project documents. Fig. 7 shows the tool architecture, which is composed of 3 key sections:

- *Data input interface*. This represents the list of forms for the data input (vessel type, lifetime, functional unit definition, inventory, etc.). This module is constructed on the basis of the proposed data framework and splits the data input into the three different life cycle phases (materials and manufacturing phase, use phase and end-of-life).
- *Impact analysis.* This encompasses the software code for the implementation of the life cycle equations and the proposed repositories (Environmental Impact Database and Costs Database). The impact analysis will be obtained correlating the data inserted previously by the use of *Data input interface* and the databases.
- *Results.* This allows to view and/or to export (spreadsheet) the obtained results.

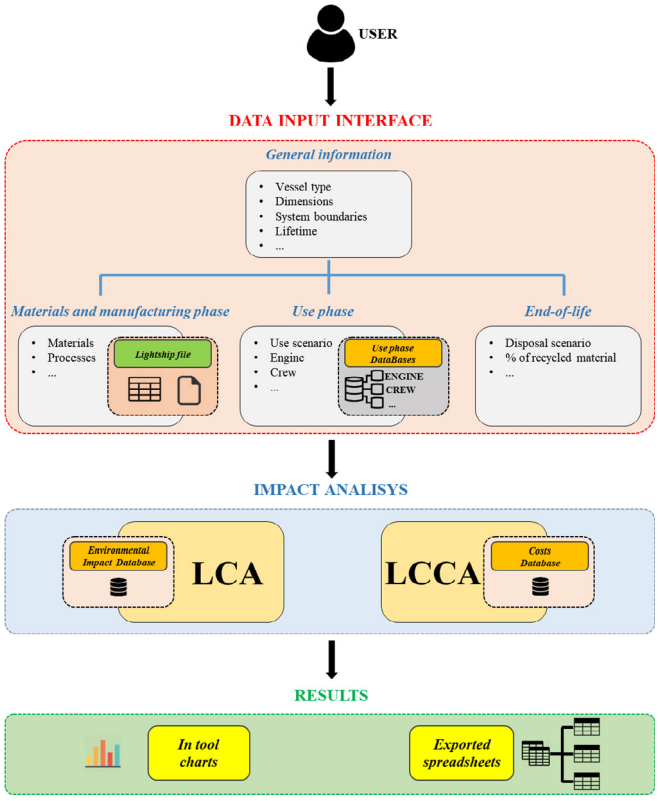


Fig. 7. Tool architecture.

The tool is designed to be used during the design phase and supports the decision-making process. It therefore requires that the parameters relating to the vessel itself (such as materials, engines used) and parameters related to the use scenario (such as mileage per year, type of maintenance) should be easily varied for a rapid comparison of project alternatives.

To fulfil the tool requirements, a set of software features need to be developed:

- Setting of the functional unit, including system boundaries (life cycle phases), lifetime (T), and reference flow (type and model of vessel). Designers and engineers can choose the most suitable boundaries and lifetime in order to fit the features of the model under development.
- Manual/automatic data input for LCI by using the proposed data framework (see Appendix A). Particularly, for those LCI items that are obtained from project documentation data sources (lightship, CAD models and datasheets), automatic data-entry allows for reducing the time needed for this phase (Fig. 8).
  An example of the algorithm used for lightship data reading is provided in Table 1.
  Input data: lightship spreadsheet

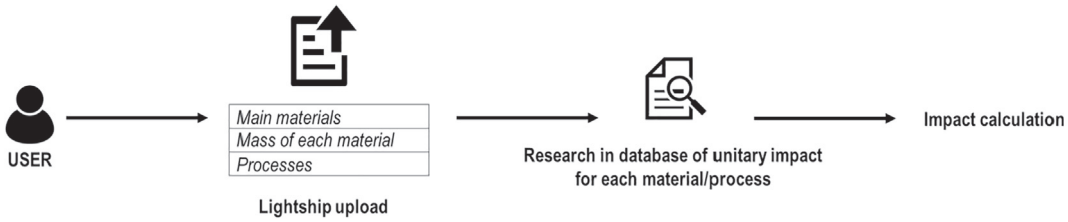


Fig. 8. Lightship data reading.

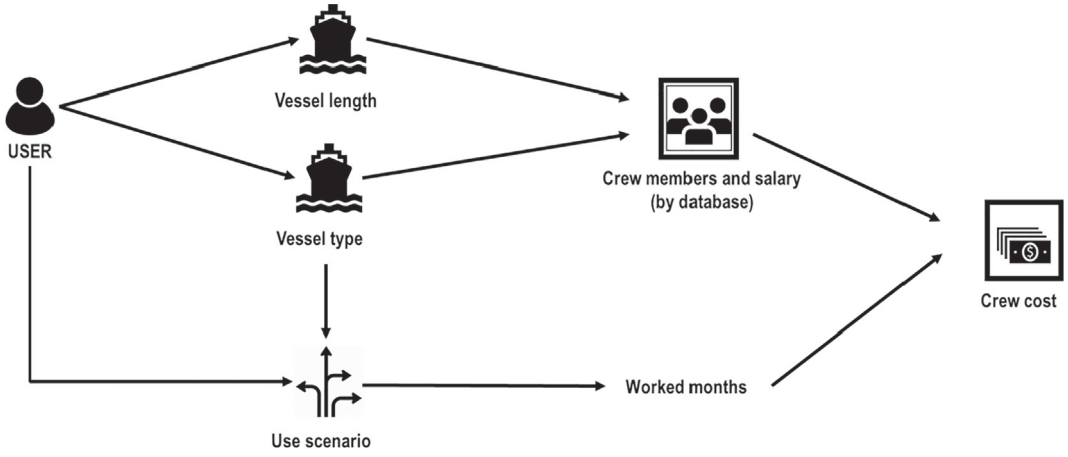


Fig. 9. Crew calculation.

Table 1
Lightship data reading algorithm.

- Pre-set of use phase groups based on vessel types and boundary conditions. This feature allows to aid engineers in the filling process of the use phase items as well as to speed up this task. The software tool interface is able to suggest values that are linked to system boundaries, vessel types, size and use scenario. Suggested values for the use phase groups are calculated by using dedicated equations and through the definition of dedicated databases, one for each use phase item. Implemented databases contain the data and information from shipyards or manufacturers, such as engine and generators fuel consumptions, crew members and associated salaries, as well as costs and consumed materials for ordinary maintenance. All suggested values within the tool interface can be edited by the user in case of inconsistencies or when more detailed values are available (Fig. 9).

An example of the algorithm developed for the crew pre-setting based on the main vessel characteristics (type, length and use scenario) is provided in Table 2.
Input data: vessel type, vessel length and use scenario
Output data: crew cost
Resolution: vessel type, vessel length and use scenario selection. Crew member's type and payrolls are obtained by vessel type and vessel length, respectively. Worked month instead is based on the use scenario selection. Finally, crew cost is obtained by multiplying the monthly salary per worked month.

Variables					
	Lightship spreadsheet declaration				
Start					
	Import file selection				
		If not imported, then			
			No action		
		If imported, then			
			Copy lightship file data Paste lightship data file in software Research of unitary impact data of materials and processes in database		
				If materials and processes are in database	
					Impact calculation: unitary impact per weight
				If materials and processes aren't in database	
					No action
Stop					

Table 2
Crew calculation algorithm.

- Possibility to select "end-of-life" options covered by international standards in this field (ISO, IMO, etc.). In the case of ship-breaking and demolition, the quantities of recycled materials can be set by assuming a certain percentage.
- Results can be further elaborated using multilevel analysis in order to focus on certain product life cycle phases or modules. This feature helps the users in the interpretation of results, identifying which phases of the life cycle are the most important or which modules are the most impactful.

Variables			
	Vessel type declaration (x_1, x_2, x_3, x_4, … x_i)		
	Vessel length declaration (y_1, y_2, y_3, y_4, … y_h)		
	Vessel use scenario declaration (z_1, z_2, z_3, z_4, … z_j)		
Start			
	Vessel type and length selection by dedicated user form		
		If vessel type = x_1 and length = y_1 then	
			Crew member = x_1
			Crew salary = y_1
		If vessel type = x_2 and length = y_1 then	
			Crew member = x_2
			Crew salary = y_1
		If vessel type = x_i and length = y_h then	
			Crew member = x_i
			Crew salary = y_h
	Use scenario selection by dedicated user form		
		If use scenario type = z_j then	
			Crew worked months = z_j
	Cost calculation		
Stop			

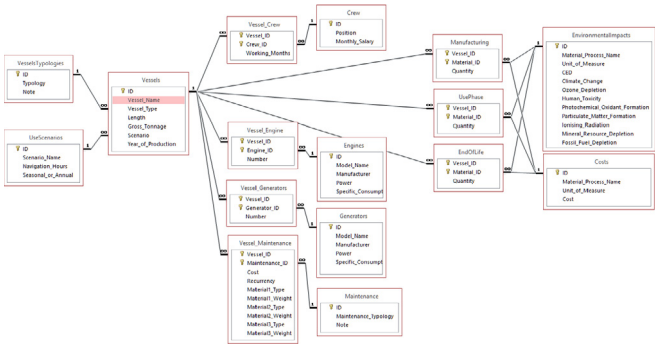


Fig. 10. Database architecture.

Output data: materials and manufacturing phase impact
Resolution: copy of material, process and weight of subgroups in lightship file. Research of material and process unitary impact in database. Total impact obtained by multiplying unitary impacts for weights.

The tool functionalities are coupled with ad hoc developed repositories for the storage of unitary impacts and costs, as well as repositories for engines' and generators' models, maintenance services, crew members, etc. Fig. 10 shows the database architecture and the relationships between the repositories.

The tables related to the vessel under analysis are automatically implemented within the software, and the required inputs must be inserted by the user.

4. Case studies

The proposed data framework was used to perform LCA and LCCA of three different yachts, designed and manufactured by an Italian shipyard. The case studies are subjected to international standards (IMO and other classification societies) dealing with statutory requirements (e.g., safety, environmental performance, rational use of materials, minimization of energy consumption, etc.). The selection of these case studies is based on the technical specifications of each model (Table 3). They differ in the materials used for the hull and superstructure (C136 is constructed using steel and aluminium, CRN43 is constructed using glass fibre-reinforced composite and P140 is fully made with aluminium), in lightweight displacement and maximum speed.

For the testing and validation of the proposed model and data framework, a software tool has been developed using Microsoft Excel and the Visual Basic for Applications (VBA) programming language. All stages of the vessel life cycle have been considered within the system boundaries. For a correct comparison, all case studies are considered with the same lifetime of 20 years, even though the CNR43 could have a longer life due to its composite

Table 3
Yacht technical specifications.

Yacht model	C136	CRN43	P140
Material	Steel/Aluminium	Composite (glass fibre-reinforced composite)	Aluminium
Length overall	49.8 [m]	42.6 [m]	42.9 [m]
Displacement lightweight	390 [ton]	280 [ton]	230 [ton]
Gross tonnage	Less than 500 [GT]	Less than 400 [GT]	Less than 350 [GT]
Maximum speed	15 [knots]	15.4 [knots]	38 [knots]

structure. The functional unit has been defined as *"the construction and disposal of a vessel for the transportation of persons and goods and/or operational activities by sea for a period of 20 years"*. All of this information together with other general input (e.g., vessel name, vessel type, gross tonnage, etc.) is set in the first tool form (Fig. 11).

Data collection has been performed on the basis of the proposed life cycle model. Inventory phase starts from the materials and manufacturing phase. It includes the data acquisition of the components and related construction processes for the eight (8) main subassemblies highlighted in Fig. 4. All construction items of each vessel are contained within the lightship-weight.XLS file, which is loaded from the company PLM system and processed by the tool. The individual group costs have been provided by the shipyard and were manually entered into the same form.

For the use phase, a navigation scenario of 500 [h/year] has been considered based on the hypothetical use of these kind of vessels, as was described by the vessels' owners. Navigation hours affect fuel consumption during the life of the vessel, and this aspect is directly related to the engines' and generators' performances. The latter are provided by the suppliers and are stored in the company PLM system as technical project documentation (engine and generator datasheet.pdf files). Fuel consumption is also a function of the speed regime. From the requirements provided by the vessels' owners, it was possible to establish three different navigation setups:

– Maximum power: 100% of maximum continuous rating (MCR).
– Cruising: 75% of MCR.
– Fuel saving: 50% of MCR.

For every setup, the typical percentage of usage is estimated as:

– Maximum power: 20% of time.
– Cruising: 30% of time.
– Fuel saving: 50% of time.

Engine and generator characteristics of the three analysed yachts are shown in Table 4.

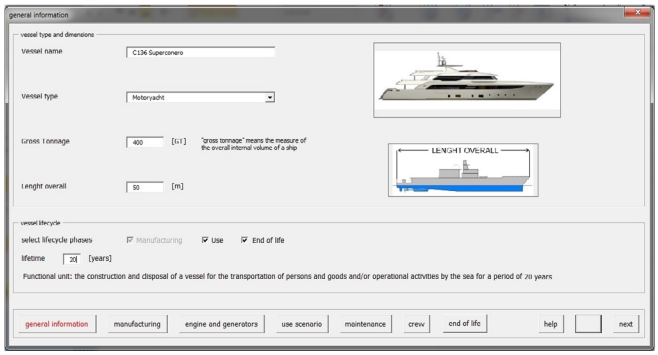


Fig. 11. Tool main form.

In addition, the requirements of the vessels' owners allow to define the use scenario which is identical for the three models: (i) yacht navigation only in the summer period (6 months) in the Mediterranean area and, (ii) yacht mooring during the winter time (6 months) in an Italian harbour (Portocervo). During the summer, all electricity consumption is provided by the generators, and water consumption is provided by the desalinator systems. In the winter, the yacht is connected to the electricity grid and the water network of the pier. The use phase data of the yacht has been included in dedicated forms as follows:

- *Engine and generators*: for choosing the type and number of engines and generators, using the datasheet contained in the database;
- *Use scenario*: to define annual operating hours, mooring port along with electricity and water consumption during the winter stop;
- *Maintenance*: for ordinary maintenance;
- *Crew*: for salaries and type of crew on board.

Use phase data are summarized in Table 5.

As described in Table 5, P140 is the most demanding vessel in terms of fuel compared to the other yachts, with approximately two times higher fuel consumption. This is due to the yacht's maximum speed of 38 [knots] required as vessel specification and obtained using 4 engines, each one with a power of 1939 [kW]. In spite of the quite different lightweight displacement and gross tonnage of C136 and CNR43, they have similar propulsion system configurations, with a small difference in engine power (1081 [kW] for C136 versus 1045 [kW] for CNR43). While lightweight displacement affects the fuel consumption because it modifies the resistance curve, the gross tonnage, which indicates the measure of the internal volume of a ship, affects the electrical consumption, which in turns requires the use of the fuel for the generators. C136 is the largest yacht in terms of internal volume, and this gives rise to a high electricity demand. CNR 43 and P140 have lower internal volumes compared to C136, and their fuel requirements for crew and ancillaries are smaller. In spite of different displacement values, C136 and CNR43 have very similar engine fuel needs owing to the defined use profile, which has been established considering the throttle/power requirements (50%, 75% and 100%). On the other hand, owing to the similar engine characteristics, C136 travels at a lower speed compared to CNR43 because of its higher weight.

By contrast, if the fuel demand is based on the nautical speed, the fuel consumption varies owing to the different power requirements. In this latter analysis, the cruising speed is fixed at 11 [knots], and the same use of 500 [h/year] of navigation is considered. Table 6 shows the engine fuel consumption in this condition. Considering the two yachts with the similar propulsion systems (C136 vs. CNR 43), CNR 43 has the lower fuel consumption compared to C136 owing to its smaller displacement.

Dismantling with material recovery is foreseen as the end-of-life for the yachts made of metals (C136 and P140), while landfilling is foreseen for the CRN43, which is mainly made of glass

Table 4
Engine and generators characteristics.

	C136	CNR 43	P140
Main engine	2 × CATERPILLAR C32 1081 [kW]	2 × CATERPILLAR C32 1045 [kW]	4 × MTU 16V2000M96 1939 [kW]
Day generator	2 × KOHLER 125 [kW]	2 × KOHLER 100 [kW]	2 × KOHLER 80 [kW]
Night generator	1 × KOHLER 55 [kW]	Not foreseen. At night one of day generators with limited power (40 [kW]) is used.	Not foreseen. At night one of day generators with limited power (30 [kW]) is used.

Table 5
Use phase data.

Use phase group		Material/Quantity			Cost		
		C136	CNR 43	P140	C136	CNR43	P140
Annual fuel consumption (MDO)	Engines	188.300 [l]	179.900 [l]	655.200 [l]	0,522 [€/l] (Bunker Index, 2018)		
	Generators	213.120 [l]	182.040 [l]	146.520 [l]			
Crew		9 people	9 people	7 people	538,000 [€/year]	468,000 [€/year]	429,000 [€/year]
Operating cost (Berthing and Insurance)		_			265,000 [€/year]	204,884 [€/year]	204,884 [€/year]
Antifouling treatment (1 per year)		131 [kg]	45 [kg]	85 [kg]	10,620 [€/treatment]	8900 [€/treatment]	9700 [€/treatment]
Safety and fire system surveys (1 per year)		_			2000 [€/treatment]	2000 [€/treatment]	2000 [€/treatment]
Anodes replacement (1 per 2 years)		150 [kg]	Not foreseen	100 [kg]	2450 [€/treatment]	_	2300 [€/treatment]
Batteries replacement (1 per 7 years)		1360 [kg]	900 [kg]	1360 [kg]	29,200 [€/treatment]	20,000 [€/treatment]	29,200 [€/treatment]
Painting (1 per 5 years)		8040 [kg]	1526 [kg]	7200 [kg]	110,500 [€/treatment]	17,630 [€/treatment]	46,000 [€/treatment]
Special surveys (1 per 5 years)		_			28,000 [€/treatment]	28,000 [€/treatment]	28,000 [€/treatment]
Water consumption (@pier)		1420 [l/day]	1136 [l/day]	994 [l/day]	0,002 [€/l] (Abbanoa, 2018)		
Electric consumption (at pier)		1200 [kWh/day]	960 [kWh/day]	840 [kWh/day]	0,25 [€/kWh] (International Energy Outlook, 2018)		

Table 6
Fuel consumption with fixed speed (11 [knots]).

	C136	CNR 43	P 140
Engine fuel consumption	62.500 [l]	57.500 [l]	105.000 [l]

fibre-reinforced composites. In particular, for C136 and P140, after the furniture removal by the vessel owner, all other parts are recycled (mainly metal such as steel, iron and aluminium) and/or landfilled (mainly plastics, woods, insulation materials, etc.). Only the percentage of the material either recycled or landfilled is included in the model. Recycling process impacts are not considered as per model definition. Table 7 summarized the end-of-life data. The proposed data were defined based on the currently available technologies in this sector. The recovery rate is considered to be the efficiency of the recycling process.

5. Results

In this section, the results obtained by the application of the proposed approach are reported. In particular, this section is structured as follows: (i) LCA/LCCA outcomes of the proposed case studies (section 5.1), (ii) LCA/LCCA results robustness with respect to the state-of-the-art analysis (section 5.2) and, (iii) benefits and advantages obtained by the adoption of the proposed approach (section 5.3).

5.1. Case study results

Results related to the environmental (LCA) and economic (LCCA) footprint of the proposed yacht models are reported in the following sections.

5.1.1. LCA results

Environmental impacts were calculated according to the defined life cycle impact assessment (LCIA) methods (ReCiPe midpoint and CED). For brevity, only the climate change indicator [ton CO2 eq.] has been reported. Other environmental indicators (metal depletion, fossil depletion, particulate matter formation, etc.) show the same qualitative trends. Fig. 12 shows a comparison of the climate change indicator between the three phases of the three analysed yachts.

The climate change indicator highlights that the use phase is the most impactful phase in the entire life cycle. This is caused by the fuel used for the engines and generators and the greenhouse gas emissions related to the fuel combustion, which are the most impactful items in this phase (see Fig. 13).

P140 is the most problematic yacht in terms of climate change [CO2 eq.] and accounts for almost two times the environmental load of the other models. Greenhouse gas emissions are directly linked to fuel consumption and combustion during the use, navigation and operational phase. On the other hand, climate change results caused by electricity and water consumption are related to the internal volume of the vessel, and their impact decreases with gross tonnage. Their impact results are respectively one order of magnitude and three orders of magnitude less than the fuel impact.

Considering the maintenance, C136 has the highest impact compared to the other two yachts. P140 and CNR43 have a smaller lightweight displacement compared to C136, and this allows for the use of a smaller quantity of antifouling and varnish because the hull is less submerged in water. Moreover, CNR43 shows the lowest impact for the maintenance item owing to its composite structure (hull and superstructure), which requires less paint than its metal equivalent (carbon steel or aluminium), and it also does not require zinc anodes for cathodic protection.

Examination of the materials and manufacturing phase, as illustrated in Fig. 14, shows that even though P140 is the lighter yacht, it is the most impactful also in this phase, owing to the material (aluminium) used for the hull and the superstructure module. Indeed, aluminium has a high environmental load caused by the transformation processes necessary to obtain the plates used in the structure fabrication. C136, which uses carbon steel, and CNR43, which uses glass fibre-reinforced composite, are next in this ranking. It is important to note that the lowest environmental

Table 7
End-of-life data.

Material	Waste treatment	Recovery rate
Iron and steel	Recycling 95%, Landfilling 5%	90% (Mikelis, 2013)
Aluminium	Recycling 95%, Landfilling 5%	97% (International Aluminium Institute, 2009)
Plastic	Recycling 50%, Landfilling 50%	88% (Schmidt, 2012)
Other materials (e.g., composites)	Recycling 0%, Landfilling 100%	Not applicable

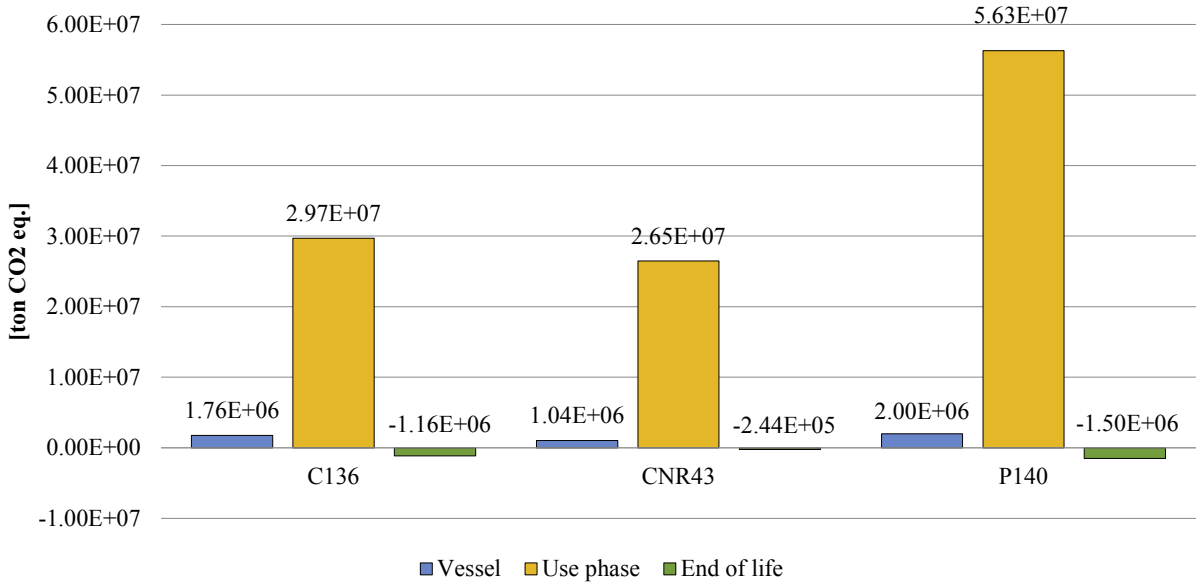
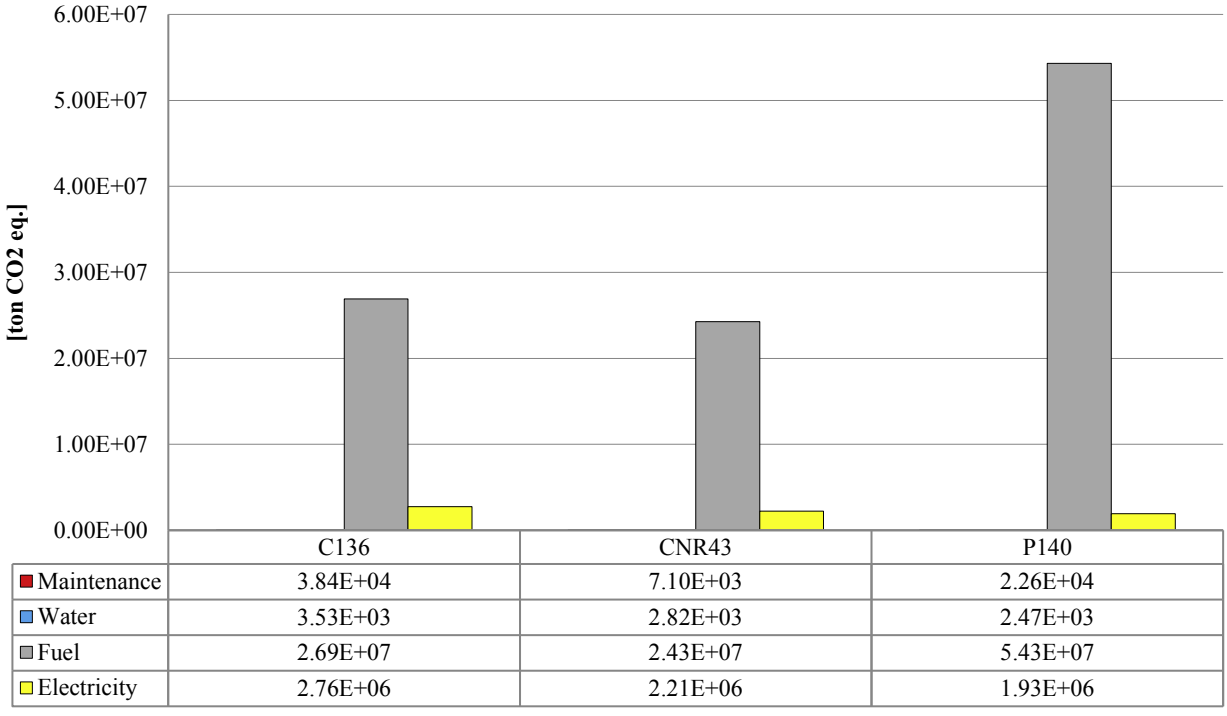


Fig. 12. LCA-Climate Change indicator for entire life cycle.



	C136	CNR43	P140
Maintenance	3.84E+04	7.10E+03	2.26E+04
Water	3.53E+03	2.82E+03	2.47E+03
Fuel	2.69E+07	2.43E+07	5.43E+07
Electricity	2.76E+06	2.21E+06	1.93E+06

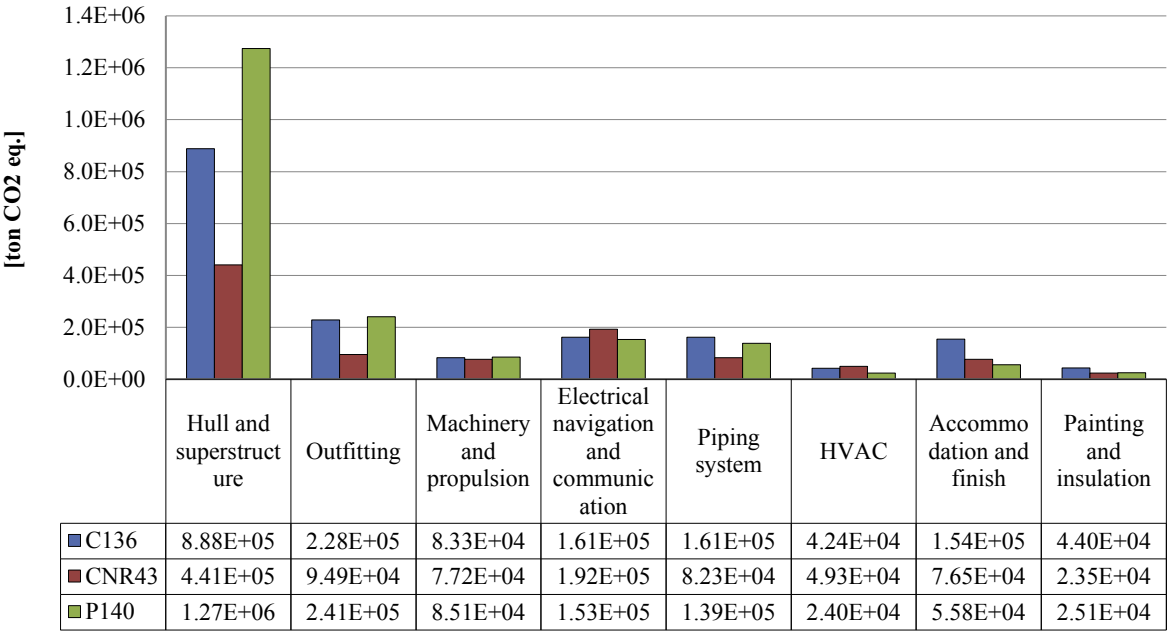
Fig. 13. LCA-Climate Change indicator for the use phase.

impact of CNR43 is derived from both (i) the nature of the raw materials (epoxy resin and short glass fibre), and (ii) the low weight of the structure realized with this material.

End-of-life phase has a negative impact (credit) for all models (C136, CNR43 and P140) due to the recovery of metal parts and structures. Focusing on the end-of-life phase of CNR43, a negative environmental impact can be observed, which is less significant than that of the other yachts (one order of magnitude). This is caused by the main structure realized with glass fibre-reinforced composite, which is considered to be a non-recyclable material and is therefore disposed in a landfill. However, other metal parts, which comprise the yacht, are assumed to be recovered, justifying the environmental credit.

5.1.2. LCCA results

Table 8 reports the overall life cycle cost results. The most impactful cost is related to the project and building phase (engineering, materials, manufacturing, shipyard management, etc.) and was summarized in the materials and manufacturing items. For the other items (e.g., maintenance, water fuel and electricity), the cost was calculated in accordance with the proposed model. Examination of the crew cost item in more detail shows that it depends on



	Hull and superstructure	Outfitting	Machinery and propulsion	Electrical navigation and communication	Piping system	HVAC	Accommodation and finish	Painting and insulation
C136	8.88E+05	2.28E+05	8.33E+04	1.61E+05	1.61E+05	4.24E+04	1.54E+05	4.40E+04
CNR43	4.41E+05	9.49E+04	7.72E+04	1.92E+05	8.23E+04	4.93E+04	7.65E+04	2.35E+04
P140	1.27E+06	2.41E+05	8.51E+04	1.53E+05	1.39E+05	2.40E+04	5.58E+04	2.51E+04

Fig. 14. LCA-Climate Change indicator for the materials and manufacturing phase.

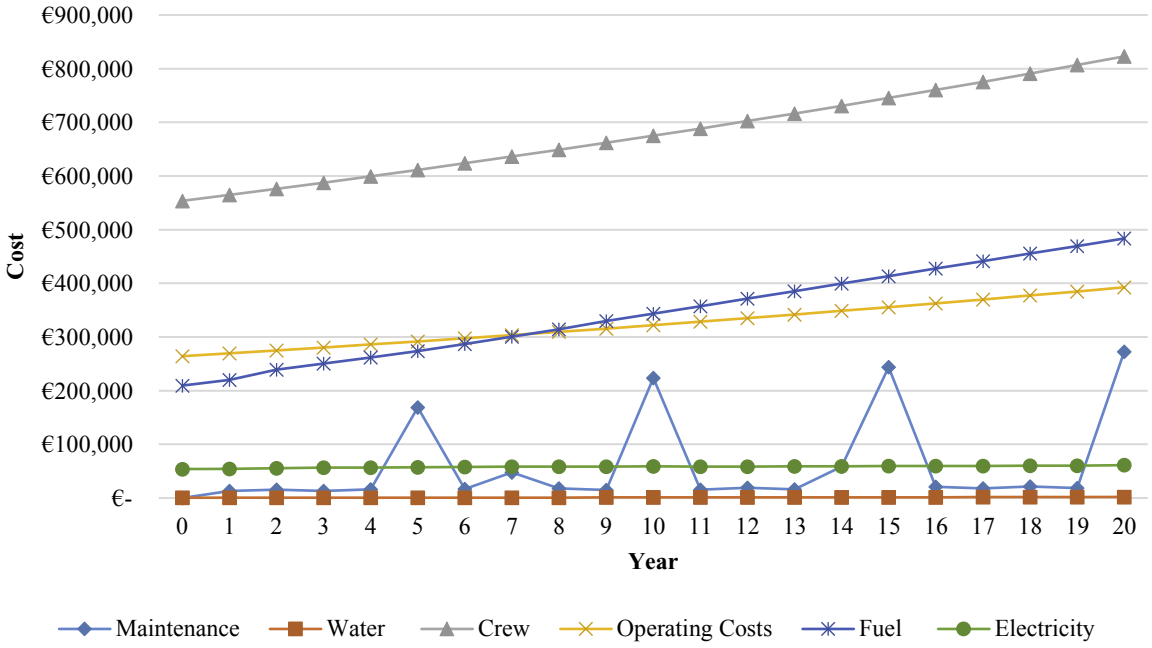


Fig. 15. Use phase trend cost (C136).

Table 8
Life cycle cost (throttle variation).

Item	C136	CNR43	P140
Materials and manufacturing	€ 16.960.744,00	€ 11.808.927,00	€ 14.192.021,00
Maintenance	€ 781.242,46	€ 424.918,44	€ 561.331,15
Water	€ 14.478,86	€ 11.583,09	€ 10.135,21
Crew	€ 9.643.587,05	€ 8.149.510,18	€ 7.368.515,46
Operating costs	€ 4.601.883,87	€ 3.567.753,48	€ 3.567.753,48
Fuel	€ 4.741.778,38	€ 4.275.420,43	€ 9.470.326,75
Electricity	€ 844.690,25	€ 675.752,20	€ 591.283,18
End-of-life	-€ 76.629,24	-€ 7.134,98	-€ 39.852,84
Total	€ 37.511.775,63	€ 28.906.729,84	€ 35.721.513,39

the yacht length and the number of the people in the crew. P140 is the cheapest vessel because it has only 7 staff members in the crew instead of 9 for the other yachts. The operating cost is also a function of vessel length, and indeed CNR43 and P140 have the same length and their operating costs are comparable. Operating costs are related to berthing and insurance cost items. In particular, berthing is the cost item referred to as the marina slip rental, while insurance is the cost of the contract with the insurance company.

The end-of-life phase is considered as a profit related to the recovery of recyclable materials. This profit depends on the lightweight displacement of the ship (see Table 3) and the quantity of recyclable materials. Indeed, C136 has the highest profit owing to its high displacement weight, while CNR43 has low profit because of its fibreglass structure, which is supposed to be disposed in a landfill (Fig. 15).

Figs. 16–18 show the trend of the running cost during use phase of the vessels. The use phase costs in these graphs are not actualized and increase every year due to inflation (assumed to be 2% every year). In the case of maintenance, several peaks are observed corresponding to the service/maintenance operations.

5.2. Result robustness

The analysis of result robustness obtained by the adoption of the

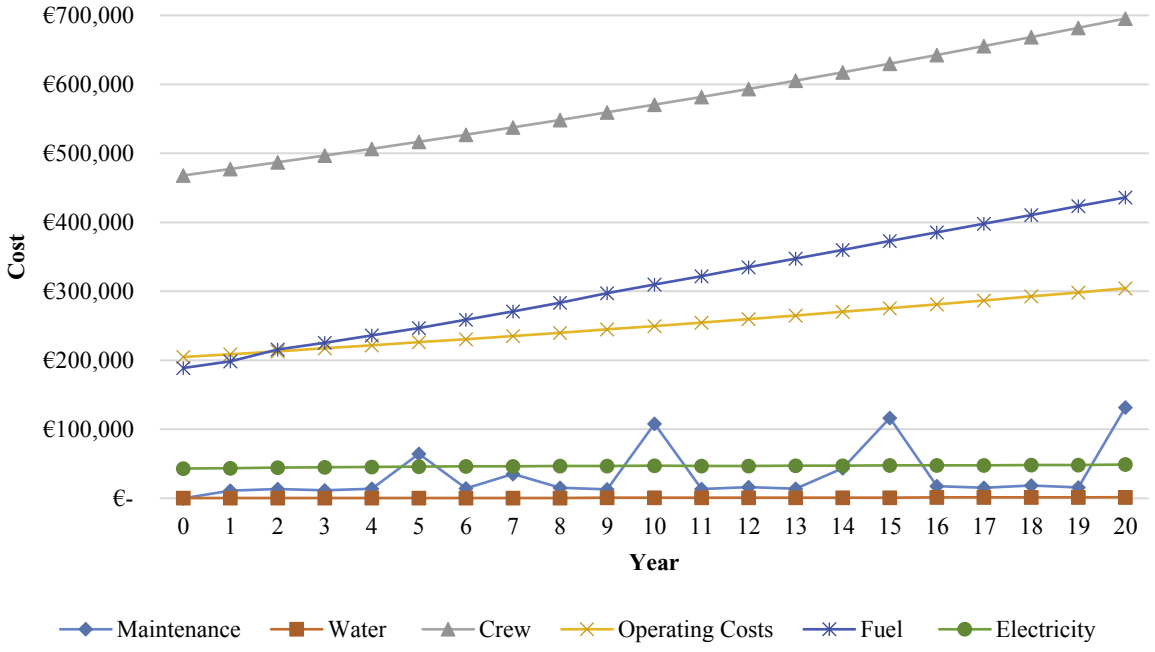


Fig. 16. Use phase trend cost (CNR43).

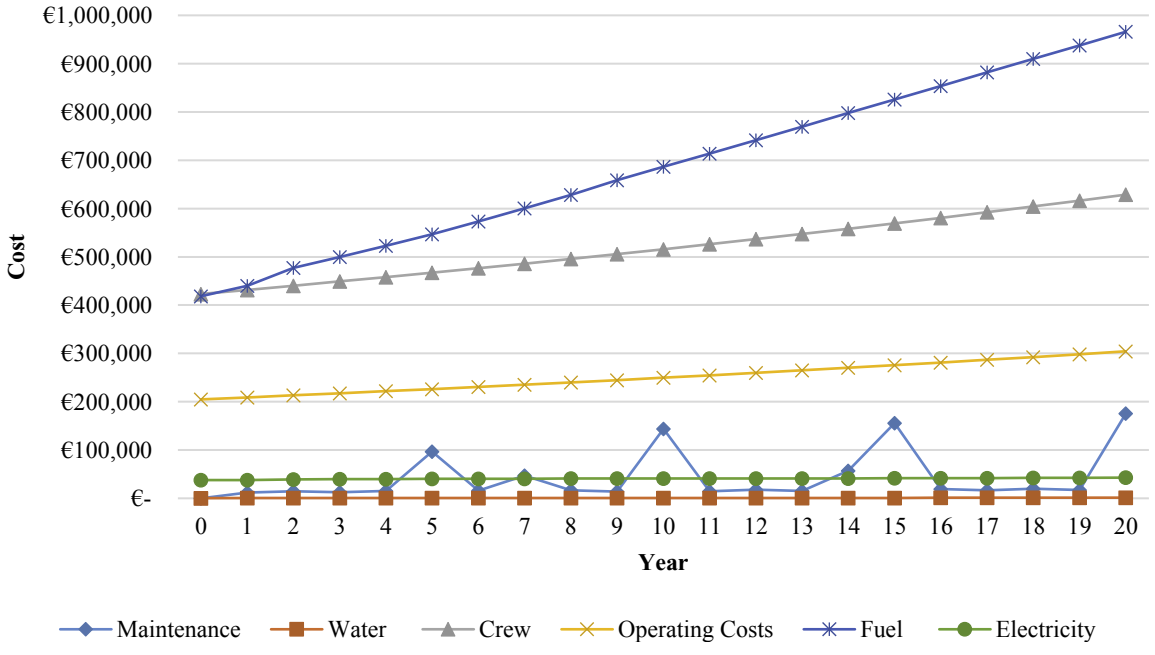


Fig. 17. Use phase trend cost (P140).

proposed model and data framework was performed in reference to the literature on the same subject. A similar trend of environmental impact assessment for several types of maritime vessels is noticed in the various studies available in the literature. Regarding motor yachts, an interesting case study proposes the comparison of two types of glass fibre-reinforced composite yachts built with different manufacturing processes: hand lay-up and vacuum infusion (Cucinotta et al., 2017). The impact assessment is evaluated with the standard method CML2001. The yachts have different lightweight displacement that affected their fuel consumption in the use phase. This result is in line with the outcome derived by the adoption of the life cycle model for the three case studies.

Another study focusing on a passenger ferry (Ro-Pax) reports a comparison between two types of ferry boats, an existing model with the hull made of carbon steel material (Tun Island Ferry) and a new version made of carbon-fibre reinforced composite (Eco Island Ferry) (Schmidt and Watson, 2013). The Eco Island Ferry is lighter than the Tun Island Ferry, allowing the use of a less powerful engine. It was observed in this study that the climate change indicator [CO_2 eq.] of the use phase is one order of magnitude higher than that of the other phases. Therefore, weight reduction and the consequent reduction of the fuel needed has high relevance for impact assessment. The environmental impact calculation in this study was carried out using the Stepwise 2006 (version 1.3) LCIA method (Weidema et al., 2007). For the global warming impact category, this method uses GWP100 [kg CO_2 eq.] which is based on the IPCC status reports as well as on the ReCiPe LCIA method used in this study.

The contribution of ship operation/use to the overall environmental load is dominant also for other vessel types. For example, ship operation of a Panamax bulker has been analysed over a period of 25 years, and it accounts for approx. 98% of the whole impact (Kameyama et al., 2007). Additionally, in the case of fishing vessels, the use phase represents approx. 92% of the total life cycle impacts (Ellingsen et al., 2002). Even if the impact assessment methods used for the estimation of environmental impacts were different in the two cases (respectively LIME end-point (Norihiro and Atsushi, 2003) and EcoIndicator95 midpoints (Goedkoop, 1995)) the outcome is qualitatively similar compared to the proposed examples.

5.3. Results and benefits of the data framework adoption

The proposed approaches (model and data framework) were tested in collaboration with the design and engineering departments of different shipyards located in the Marche region (Italy), which are building a variety of different vessel types ranging from yachts to cruise ships. Shipyard design engineers were involved in the project and in the implementation of the life cycle model. Their contribution were useful for the development of the tool and the framework because they helped us in the definition of the input parameters and to find reliable data sources among the project documentation. Furthermore, they provided feedback on the tool usability. Owing to the results of the analysis, it was possible to determine that the use phase is the most impactful phase of the yacht life cycle; in particular, the designers decided to focus on the reduction of fuel consumption in order to reduce the total environmental impact.

The implementation of the proposed model and the developed data framework within the tool allows for a simpler and faster analysis of the environmental and cost assessment of a maritime vessel through its life cycle. First, the inventory phase is considerably faster relative to a dedicated analysis developed following the ISO standard and a dedicated LCA software. The tool was adopted within the technical department of the shipyard and engineers were able to process the lightship-weight document (.XLS file) in about a minute (the processing speed depends on the dimensions of the file itself). In addition, data entry for the other phases, which are use scenarios (e.g., use phase) and end-of-life options, was still fast owing to the suggestions provided by the tool itself using dedicated algorithms. The same activity carried out by using a dedicated LCA tool would take several hours because of the high number of items that must be input within the software.

Considering the C136 model, life cycle assessment outcome achieved by the adoption of the proposed method (model, data framework and tool) was compared to a dedicated analysis performed by environmental experts (academia researchers) and using commercially available LCA software (SimaPro8 with EcoInvent 3.1 database). The goal and scope definition of this analysis were based on the same ISO standards (ISO 14040 and ISO 14044), and it was defined in accordance with the purpose of the analysis performed with the proposed method, including the same functional unit, system boundaries, and reference flow.

In this latter analysis, the same documentation was used for the input data. However, by comparing the numerical values of environmental impacts, it can be noticed that the estimated error between the two analyses remains generally low, except in the manufacturing phase where a difference of 6.3% was obtained. This gap is the result of two main approximations adopted within the tool: (i) particular materials (e.g., the ones used in the furniture and decoration): are not present in the developed impact assessment database and were neglected in the analysis, and (ii) material scrap recovery was estimated as a percentage of the total mass. However, this can be considered an acceptable error for the performed analysis considering that the materials and manufacturing phase accounts for less than 5% of the overall life cycle. Table 9 shows results for the differences between the two analyses.

On the other hand, LCCA analysis does not show any difference in the results because the proposed model adopts the same algorithms and cost items of the available in-house tool for the assessment of the total cost of ownership. One issue related to the developed software tool is related to the calculation of some cost items such as manufacturing costs. For a particular maritime vessel (e.g., yachts), it is difficult to set production cost models because they are not built in series but tailored to the needs of the customer. To solve this problem, manual input of some items is allowed.

6. Discussion and conclusions

This paper proposes a model and a specific data framework for the complete life cycle evaluation of maritime vessels. The model enables benchmark analysis and comparison between different design solutions, considering both environmental impact and costs. The model takes into account the vessel's building (materials and manufacturing processes), the operational use phase and the end-of-life. For these reasons, the presented model can be considered a useful tool for decision-making strategies and allows the designer to choose between different solutions in the early phase of the design process in order to reduce life cycle environmental impacts and costs.

The data framework enables to standardize the LCI by identifying the data required and providing the mathematical relationships necessary to obtain the missing data.

The model and the data framework provide a basis for the development of specific software tools for the life cycle analysis of a vessel, eliminating the subjectivity problem in the analysis of this type of object. Indeed, since there are no common life cycle regulations in the naval field, the currently used software presents the problems of being customized by the company needs (Sharma and Kim, 2010) and is mainly used after the design (Gratsos et al., 2009).

Table 9
Difference between tool and SimaPro8 (C136).

	Climate change [ton CO2 eq.]			CED [MJ]		
	Materials and manufacturing phase	Use phase	End-of-life	Materials and manufacturing phase	Use phase	End-of-life
Tool	1,76E+03	2,97E+04	−1,16E+03	2,01E+07	4,47E+08	−1,22E+07
SIMAPRO8	1,87E+03	2,99E+04	−1,19E+03	2,13E+07	4,48E+08	−1,23E+07
Difference [%]	6,3%	0.7%	2,6%	6,0%	0,2%	0,8%

The software has a simple architecture, contains a set of useful features and guides the user in the data-entry. For these reasons, the tool does not require the involvement of experts and skilled users. Interpretation of the result, however, still requires a skilled user who will be able to determine the areas that should be focused on in order to reduce the impacts. In addition, the software interface shows only basic information, allowing the skilled user to view, on request, the most advanced parameters of the analysis and then giving him the ability to either modify these values or leave the preset values. A tool with the characteristics mentioned above was developed on the basis of the excel VBA application. VBA is compatible with existing IT systems because it is implemented in a standard spreadsheet.

Knowledge transfer regarding this work from shipbuilding to other industrial fields is possible. The first important aspect that can be transferred to other industrial sectors is the intention to create a structured data framework and data models that are able to standardize the items and the required data for life cycle analysis. A data framework allows the creation of repeatable and consistent flow of information aiming at the comparison of different alternatives while maintaining the same level of detail. Another interesting aspect that can be transferred is the way to “automatically” read project documentation with the aim to address the problem of inventory collection, which is subject to errors and requires a huge amount of time. The specificities of each industry need to be carefully analysed, and the data framework should be able to address them, including the location (project files) in which the information is stored. Industrial fields that could benefit from this research include (i) other transportation industries (e.g., aviation and railway), (ii) building and construction, and (iii) manufacturing plants (e.g., appliances, consumer's goods, etc.).

Future studies are necessary to incorporate the data framework into a general ship product model data that can be used as a reference for a specific PLM for these products, where a specific Life Cycle module can be found. Another important aspect for future study is the introduction of probabilistic data and the performance of statistical analysis (e.g., Monte Carlo) in order to consider the data uncertainties related to the economic and environmental scenarios of the long lifespan of the vessels.

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Appendix A. Data framework

Materials and manufacturing phase

Group	Subgroup	Item	Data required	Data type	Data input	Data source
Hull and superstructure	Hull blocks	Metallic plates	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Hull and superstructure	Hull blocks	Bulwark on main deck	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Hull and superstructure	Hull blocks	Metal cutting	Technology Length	String Numeric	Manual	CAD models
Hull and superstructure	Hull blocks	Metal welding	Technology Length	String Numeric	Manual	CAD models
Hull and superstructure	Hull blocks	…*	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Hull and superstructure	Chain locker	Flooring	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Hull and superstructure	Chain locker	Internal side covering	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Hull and superstructure	Chain locker	…	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Hull and superstructure	…	…	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Outfitting	Anchoring & mooring equipment	…	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Outfitting	…	…	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Machinery and propulsion	…	…	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Electrical navigation and communication	…	…	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Piping system	…	…	Material	String		

(*continued*)

Group	Subgroup	Item	Data required	Data type	Data input	Data source
			Mass	Numeric	Automatic or manual	Lightship-weight
HVAC	…	…	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Accommodation and finish	Household equipment	Fridge (if available in the costs and environmental impacts databases)	Model	String	Automatic or manual	Lightship-weight
Accommodation and finish	…	…	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Painting and insulation	…	…	Material Mass	String Numeric	Automatic or manual	Lightship-weight
Electrical navigation and communication	…	…	Material Mass	String Numeric	Automatic or manual	Lightship-weight

*: Almost all the items considered for the Manufacturing phase require only "Material" and "Mass" data; the only items that require different data are manufacturing processes (such as "Metal cutting" and "Metal welding"); these items, however, as a first approximation, are considered only for the "Hull and superstructure" group. For this reason, for briefness, all other items have not been reported, and in the table are simplified with the symbol "…".

Since the items of the lightship may be not known with certainty at the moment of the analysis, some simplification must be made. In particular, the presence and the characteristics of many by-products, such as home appliances, are subjective and depend heavily on the ship-owner; for this reason, these items are not considered in the framework. Electrical navigation devices, instead, are always on board, and thus they are modelled in the framework using the generic material "Electrical equipment" (EcoInvent).

Use phase

Group	Data required	Data type	Data input	Data source
Fuel and lubricating oil	Navigation hours	Numeric	Automatic (from scenarios' databases) or manual	Scenario
Fuel and lubricating oil	Engines and generator efficiency	Numeric	Automatic (from scenarios' databases) or manual	Motors datasheet
Fuel and lubricating oil	Type of fuel	String	Automatic (from scenarios' databases) or manual	Motors datasheet
Fuel and lubricating oil	Offshore electric consumption	Numeric	Automatic (from scenarios' databases) or manual	Scenario
Crew	Crew's members	String	Automatic (from scenarios' databases) or manual	Scenario
Crew	Salaries, payroll services, medical costs, food costs, uniforms costs…	Numeric	Automatic (from scenarios' databases) or manual	Market
Operating costs	Berthing cost per day	Numeric	Automatic (from scenarios' databases) or manual	Market
Operating costs	Insurance cost per year	Numeric	Automatic (from scenarios' databases) or manual	Market
Maintenance	Recurrence of the treatments	Date	Automatic (from scenarios' databases) or manual	Scenario/ Regulations
Maintenance	Treatments' cost	Numeric	Automatic (from scenarios' databases) or manual	Market
Maintenance	Materials required (mass)	Numeric	Automatic (from scenarios' databases) or manual	Scenario/ Regulations
Water consumption	Water consumption during berthing	Numeric	Automatic (from scenarios' databases) or manual	Scenario
Electric consumption	Electric consumption during berthing	Numeric	Automatic (from scenarios' databases) or manual	Scenario

Fuel quantity for propulsion can be calculated as follow (fuel for electricity generation can be calculated in a similar way):

$$C_f = l/h \times N_e \times h$$

Here:

C_f: fuel consumption [l];
l/h: Engine efficiency [l/h];
N_e: Number of engines;
h : Navigation hours [h].

Emissions derived by fuel combustion can by calculated as follow:

$$E_p = \frac{e_p \times C_f}{\rho_f}$$

Here:

E_p: Emission of a single polluting element (e.g. CO, CO_2, etc.) [kg];
e_p: Emission indices for a single polluting element [g/kg];
ρ_f: Fuel density [kg/l];
C_f : Fuel consumption [l].

End-of-life

Material	Data required	Data type	Data input	Data Source
Aluminium	Recycling percentage	Numeric	Automatic (from scenarios' databases) or manual	Scenario
	Incineration percentage	Numeric		Scenario
	Landfill percentage	Numeric		Scenario
Carbon fibre	Recycling percentage	Numeric	Automatic (from scenarios' databases) or manual	Scenario
	Incineration percentage	Numeric		Scenario
	Landfill percentage	Numeric		Scenario
Copper	Recycling percentage	Numeric	Automatic (from scenarios' databases) or manual	Scenario
	Incineration percentage	Numeric		Scenario
	Landfill percentage	Numeric		Scenario
Inert	Recycling percentage	Numeric	Automatic (from scenarios' databases) or manual	Scenario
	Incineration percentage	Numeric		Scenario
	Landfill percentage	Numeric		Scenario
PVC	Recycling percentage	Numeric	Automatic (from scenarios' databases) or manual	Scenario
	Incineration percentage	Numeric		Scenario
	Landfill percentage	Numeric		Scenario
Plastics	Recycling percentage	Numeric	Automatic (from scenarios' databases) or manual	Scenario
	Incineration percentage	Numeric		Scenario
	Landfill percentage	Numeric		Scenario
Resins	Recycling percentage	Numeric	Automatic (from scenarios' databases) or manual	Scenario
	Incineration percentage	Numeric		Scenario
	Landfill percentage	Numeric		Scenario
Steel	Recycling percentage	Numeric	Automatic (from scenarios' databases) or manual	Scenario
	Incineration percentage	Numeric		Scenario
	Landfill percentage	Numeric		Scenario
Textile	Recycling percentage	Numeric	Automatic (from scenarios' databases) or manual	Scenario
	Incineration percentage	Numeric		Scenario
	Landfill percentage	Numeric		Scenario
Wood	Recycling percentage	Numeric	Automatic (from scenarios' databases) or manual	Scenario
	Incineration percentage	Numeric		Scenario
	Landfill percentage	Numeric		Scenario
…	Recycling percentage	Numeric	Automatic (from scenarios' databases) or manual	Scenario
	Incineration percentage	Numeric		Scenario
	Landfill percentage	Numeric		Scenario

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